Searching for New Physics in the Neutrino Sector

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Neutrinos and precision

- experiments designed for high precision measurements
  e.g. DUNE, short baseline program at Fermilab, etc.

- very high statistics data
  e.g. atmospheric neutrinos in IceCube Deep Core/PINGU

- high precision determination of standard neutrino properties

- sensitivity to new neutrino properties and other new physics

  require high precision measurements as well as
  high precision theoretical understanding of many issues
  (e.g. interaction cross sections, analysis framework)

- here concentrate on neutrino oscillations

Neutrino oscillations

- consistent picture of three flavor oscillations from many experiments:

  solar neutrinos, atmospheric neutrinos,

  reactor neutrinos, accelerator neutrinos

- with some "anomalies"

  LSND, MiniBooNE, Reactor, Gallium

- Three-flavor mixing matrix $U = R_{23}\, K\, R_{13}\, K^*\, R_{12}$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\theta_{12} = \theta_{sol} \qquad \theta_{13} = \theta_{reactor} \qquad \theta_{23} = \theta_{atm} \qquad \delta$$

$$\Delta m^2_{21} = \Delta m^2_{sol} \qquad \Delta m^2_{32} = \Delta m^2_{atm}$$

Precision?

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\mathrm{CP}}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Esteban, I., Gonzalez-Garcia, M.C., Maltoni, M. et al.
J. High Energ. Phys. (2017) 2017: 87.
www.nu-fit.org

Neutrinos in the Standard Model and beyond

- Neutrino mass and mixing: physics beyond SM.
- Non-trivial extension:
  - add right handed neutrino to SM (like for other SM fermions)
  - add Yukawa coupling to Higgs $Y_\nu \bar{L} H N_R$
    (like for other SM fermions)
  - BUT Majorana mass term $M_R \overline{N_R^c} N_R$ allowed by SM symmetries
    (unlike for other SM fermions)

Need to consider at least:

new implications of Majorana neutrinos

or

new symmetry to forbid Majorana mass term

-> new interactions, new phenomena, etc.

Neutrino mass and mixing: physics Beyond Standard Model

Simplest scenario:

right-handed neutrino: Yukawa: $Y_\nu \bar{L} H N_R$ and $M_R \overline{N_R^c} N_R$

Majorana mass $M > v$ $\longrightarrow$ see-saw mechanism

$$m_1 \sim M \qquad m_2 \sim \frac{Y^2 v^2}{M}$$

$$Y_t \sim 1 \qquad M \sim M_{GUT}$$

$$Y_e \sim 10^{-6} \qquad M \sim TeV$$

Other scenarios:

see-saw like: $m \sim \dfrac{Y'^2 v'^2}{M'}$

v' and M'can both be much smaller

Different scenarios

KeV, MeV, GeV discussed in different contexts

(hidden sectors, dark matter connections, etc.)

flavor symmetries, etc.

Searching for new physics

- The new physics is there! (somewhere)
- How do we find it/understand it?
- Different scenarios have different observational consequences
- We know a lot more about neutrinos than we did 20 years ago, but we do not yet know for sure what to look for and where

→ need to keep looking everywhere

- Many approaches:
  - Explicit model building
  - Effective theories/operators, general parametrizations
  - Measure everything you can and maybe something comes up
  - Some combinations of these
  - Detailed studies of sensitivities for specific experiments (design a better experiment)
  - Study how to combine data from different experiments or look at completely new set of observables and connections to other physics (e.g collider, astrophysics, cosmology) (get more from the data you have/can get)

Non-Standard neutrino Interactions (NSI)

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

$\boxed{\text{L. Wolfenstein}}$
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\rho\nu_\beta)(\bar{f}\gamma_\rho P f)$$

Non-Standard neutrino Interactions (NSI)

- new neutrino interactions, smaller than SM ones can be parametrized as $\epsilon_{\alpha\beta}$

$$\mathcal{L} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f} \gamma_\rho P f)$$

- Effective parametrization in terms of $\epsilon_{\alpha\beta}$ very general: can come from different types of underlying physics
- E.g.:
  - Higher dimensional operators: suppressed by scale M
  - effects of a sterile neutrino at energies much lower than its mass look like $\epsilon_{\alpha\beta}$
  - leptoquarks
- If you can constrain general $\epsilon_{\alpha\beta}$, many models can map their parameters onto $\epsilon_{\alpha\beta}$

Neutrino oscillations: production, detection and propagation

Propagation effects (linear): long distance, high density

Effects can be higher at high energy

NSI: matter effect

$$H_{I,NSI} = V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}} \\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}} \\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{\substack{f=e,u,d \\ P=L,R}} \epsilon_P^{\alpha\beta,ff} \frac{n_f}{n_e}$$

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \bar{\nu}_\alpha \gamma_\mu \nu_\beta \left(\epsilon_L^{\alpha\beta,ij} \bar{f}_L^i \gamma^\mu f_L^j + \epsilon_R^{\alpha\beta,ij} \bar{f}_R^i \gamma^\mu f_R^j \right) + h.c.$$

NSI: constraints

M.C. Gonzalez-Garcia, M. Maltoni, JHEP 1309 (2013) 152

		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\ [-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_{D}	-0.140	$[-0.24, -0.01]$	$\oplus\ [+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\ [+0.34, +0.67]$
ε^u_{N}	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\ [-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_{D}	-0.145	$[-0.25, -0.02]$	$\oplus\ [+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\ [+0.42, +0.70]$
ε^d_{N}	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

Interesting range: already below G_F

want better sensitivity

better understanding of effects

long distance, high density, high energy could help

Neutrino Telescopes

- Present: IceCube(+DeepCore), SuperKamiokande
  Future: extensions (PINGU, HyperKamiokande)
  + new experiments/techniques

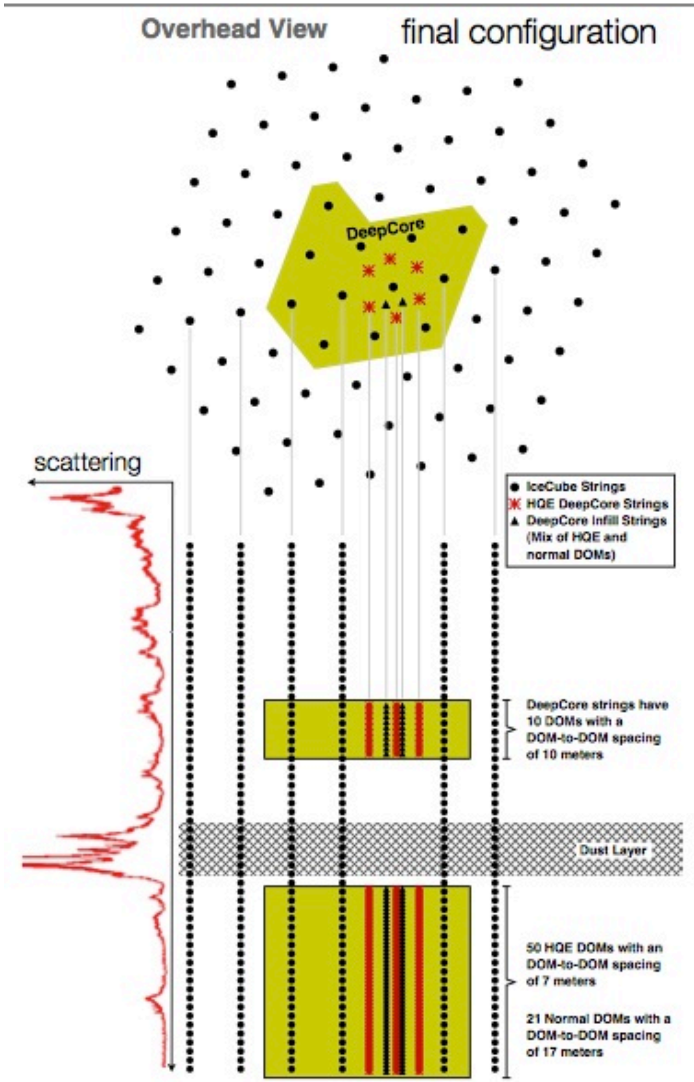
- High energy neutrinos from astrophysical sources detected!
  - Want to understand:
    - astrophysics:
      - origin, source characteristics, relation to cosmic rays, gamma rays, etc.
    - physics:
      - sensitivity to new interactions
      - tests of fundamental symmetries (Lorentz, etc.)

- Dark matter annihilation

IceCube Deep Core

- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center

- 8 special strings, 72m IS, 7m DOM spacing
- ~ 5x higher effective photocathode density
- ~ 20Mton
- IceCube's top and outer layers: active veto



- Up to 100,000 events/year! Use them!
- Energy range 10-40 GeV great for oscillation physics
- Statistics compensate for systematics for many issues
  - Use energy and angular distributions sensitive to physics
  - Normalizations can be determined from data

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Neutrino mass hierarchy extraction using atmospheric neutrinos in ice

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We show that the measurements of 10 GeV atmospheric neutrinos by an upcoming array of densely-packed phototubes buried deep inside the IceCube detector at the South Pole can be used to determine the neutrino mass hierarchy for values of $\sin^2 2\theta_{13}$ close to the present bound, if the hierarchy is normal. These results are obtained for an exposure of 100 Mton years and systematic uncertainties up to 10%.

- Data already there: need the right tools to analyze it

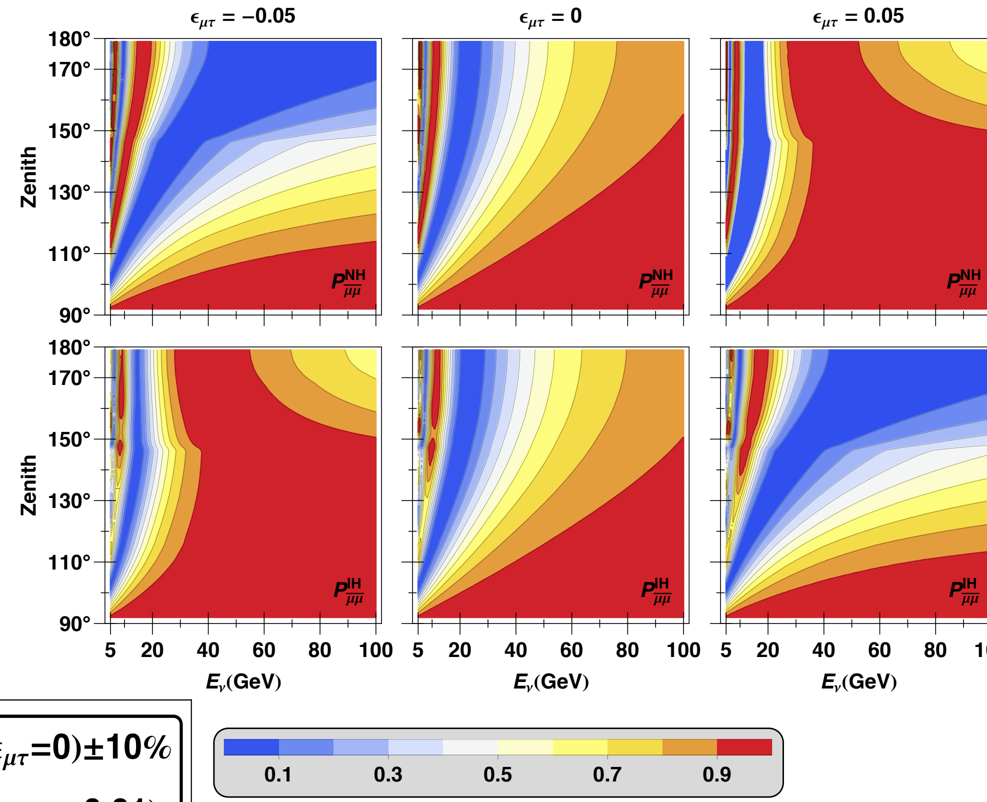
ICDC/PINGU

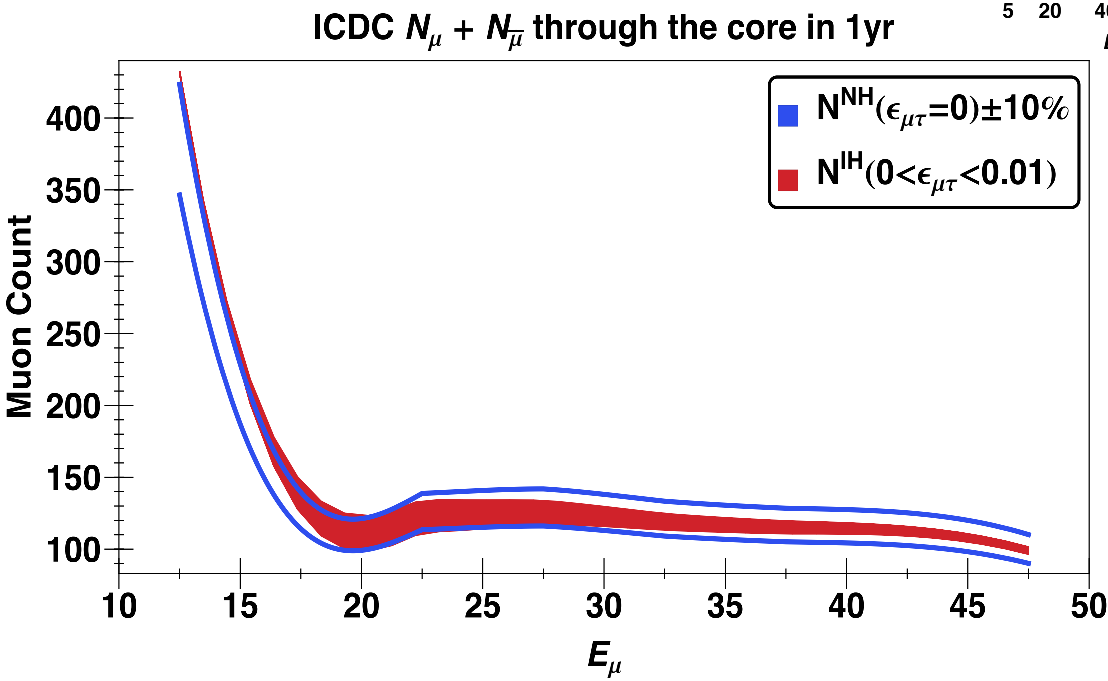
- mass hierarchy (O.Mena, I.Mocioiu, S.Razzaque, Phys. Rev. D78(2008) 093003)
- precision on all parameters
  (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D82 (2010) 093001)
- tau neutrino appearance
  (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D81 (2010) 113008)

- new physics in neutrino sector
  - large range of energies
  - large range of distances
  - high densities: matter effects

NSI: understanding degeneracies

- Mu-Tau sector



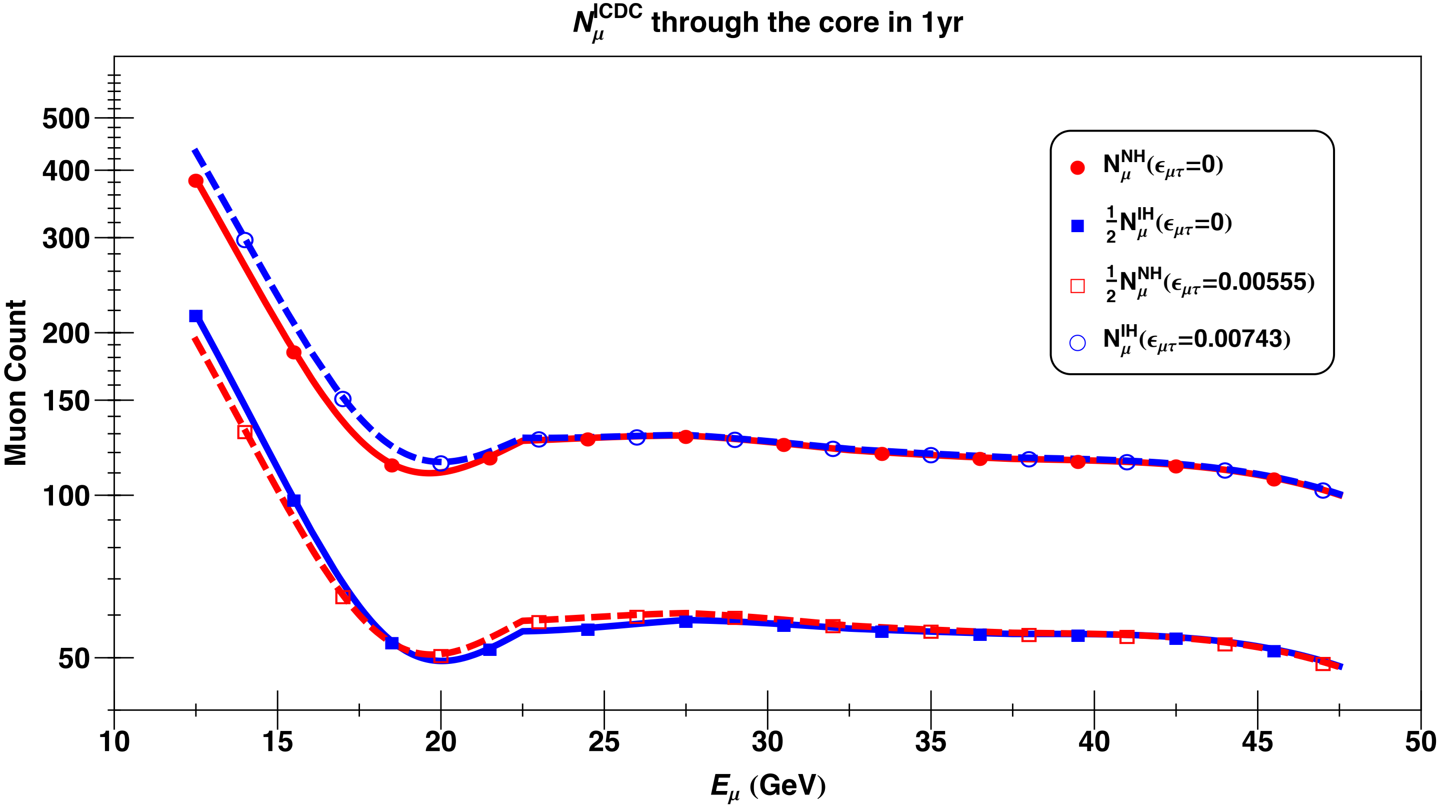


I.Mocioiu, W.Wright, arXiv:1410.6193,
Nucl.Phys. B893 (2015) 376-390

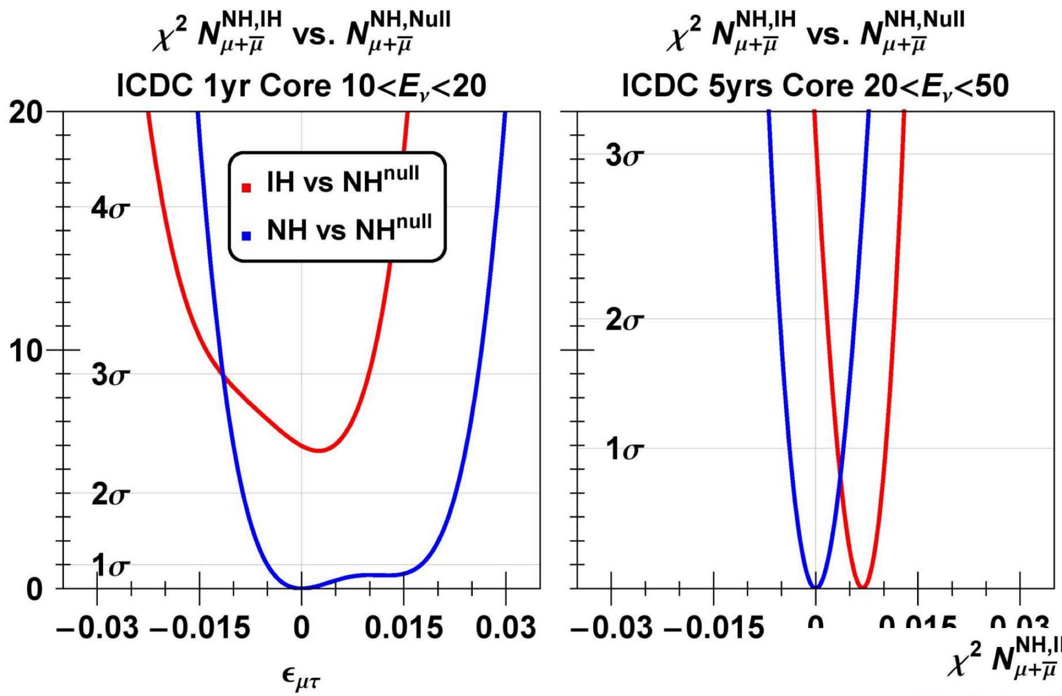
NSI: understanding degeneracies

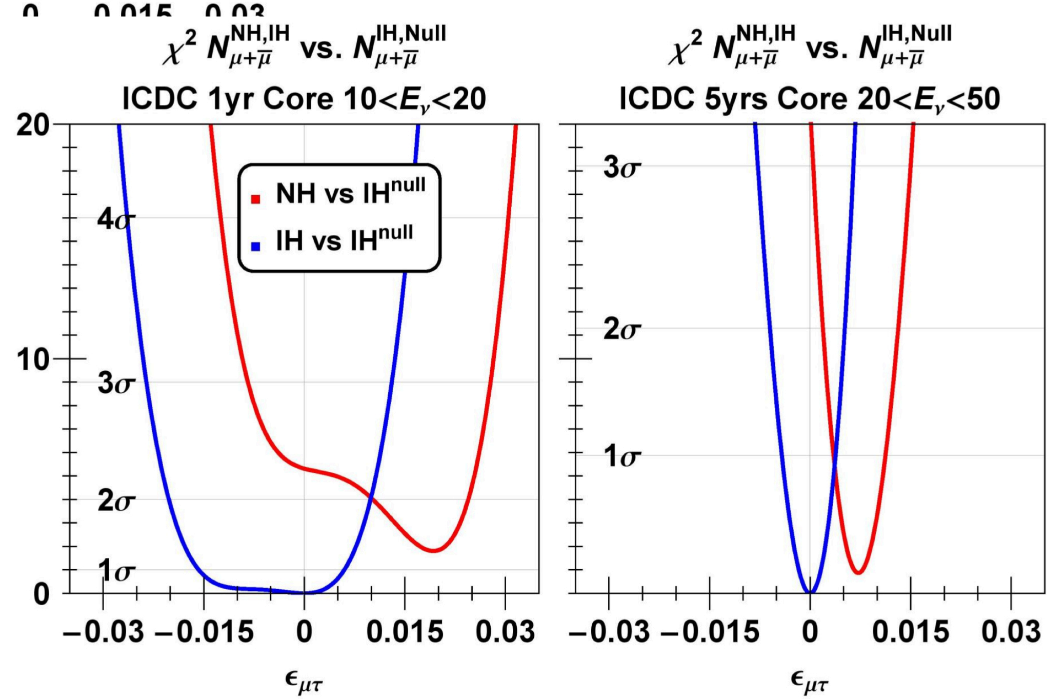
$$\Delta m^2_{21} = \theta_{12} = \theta_{13} = \delta_{cp} = \epsilon_{\alpha\beta\neq\mu\tau} = \delta_{\mu\tau} = 0 \quad \theta_{23} = \pi/4$$

$$P_{\mu\mu} = \cos^2\left(L\left(\frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau}\right)\right)$$



NSI: breaking degeneracies





NSI: breaking degeneracies

- Long baseline neutrino experiments

  DUNE: ν_e appearance

  matter effect, little sensitivity to $\epsilon_{\mu\tau}$

$$\Delta m_{31}^2 \to -\Delta m_{31}^2 + \Delta m_{21}^2$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$\epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2$$
$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})$$
$$\epsilon_{\alpha\beta} \to -\epsilon_{\alpha\beta}^* \quad (\alpha \neq \beta)$$

Coloma and Schwetz, 1604.05772
Liao, Marfatia, Whisnant 1602.08766
...

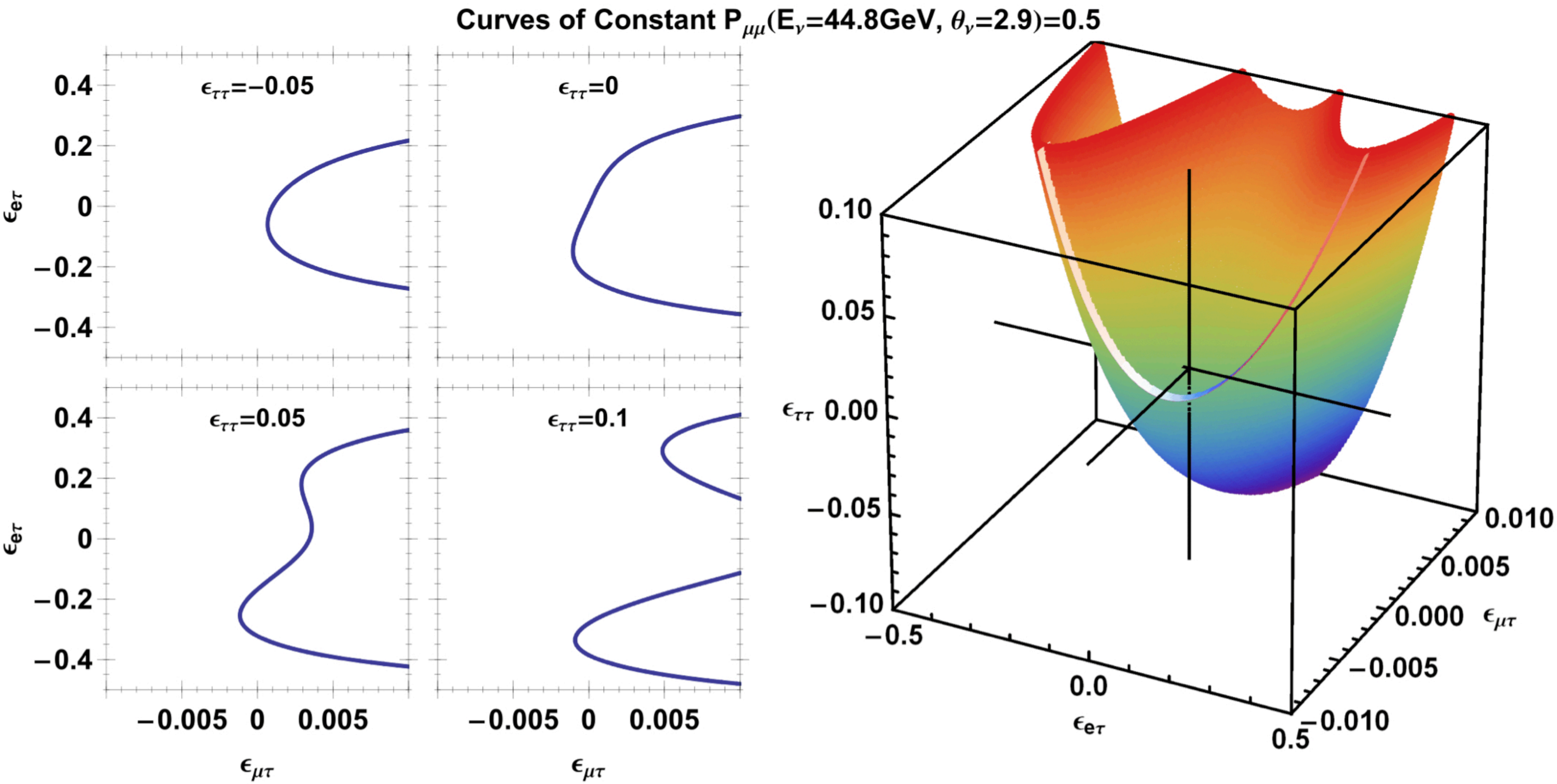
NSI: understanding degeneracies

All $\delta = 0,\ \Delta m_{21}^2 = \epsilon_{e\mu} = 0$ and $\Delta = \Delta m_{31}^2/(4E_\nu)$

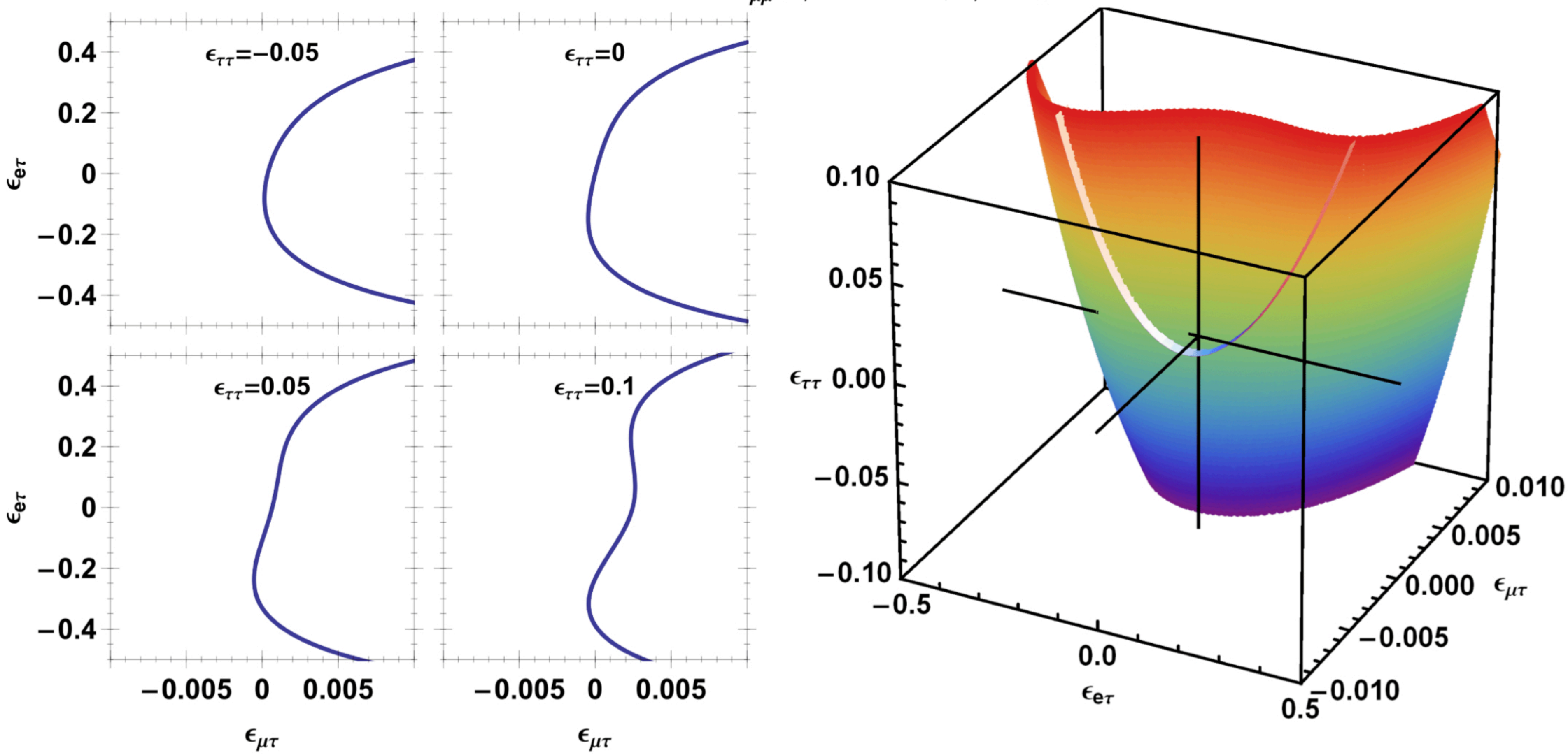
$$H = \begin{pmatrix} V_{cc}(1+\epsilon_{ee}) + 2\Delta s_{13}^2 & \Delta s_{2\cdot 13} s_{23} & V_{cc}\epsilon_{e\tau} + \Delta s_{2\cdot 13} c_{23} \\ \Delta s_{2\cdot 13} s_{23} & V_{cc}\epsilon_{\mu\mu} + 2\Delta c_{13}^2 s_{23}^2 & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2\cdot 23} \\ V_{cc}\epsilon_{e\tau} + \Delta s_{2\cdot 13} c_{23} & V_{cc}\epsilon_{\mu\tau} + \Delta c_{13}^2 s_{2\cdot 23} & V_{cc}\epsilon_{\tau\tau} + 2\Delta c_{13}^2 c_{23}^2 \end{pmatrix}$$

- Matter resonance at multiple energies, depending on NSI parameters

NSI: understanding degeneracies



Curves of Constant $P_{\mu\mu}(E_\nu=100.\text{GeV}, \theta_\nu=2.7)=0.9$



NSI: breaking degeneracies

- need multiple observables/
  independent measurements of hierarchy
  - ICDC/PINGU: ν_μ survival
    large matter effect, good sensitivity to $\epsilon_{\mu\tau}$, high statistics
    energy distribution
  - NOVA/DUNE (LBNE): ν_e appearance
    matter effect, less sensitivity to $\epsilon_{\mu\tau}$
    different degeneracies, with different parameters
  - JUNO (other long baseline reactor) : $\bar{\nu}_e$ disappearance
    interference of mass scales, no matter effect/NSI
  - Neutrinoless double beta decay, cosmology, etc.

→ measure hierarchy and $\epsilon_{\mu\tau}$ in consistent global fit

Neutrinos and New Physics

- Model Building
  - explicit theoretical models that generate large NSI and are consistent with all other constraints
- NSI in other contexts
  - matter effects only probe vector-like interactions
  - what about others?
  - scattering experiments (high precision or high energy) can probe other NSI structures.
  - back to pre-SM tests at 1% of weak interaction!
  - tests at highest energy (e.g. IceCube astrophysical nus)

    hidden source matter effect: Mena, Mocioiu, Razzaque (2007)

    Smirnov et. al. , Winter et. al. (2010)
  - supernovae + other astrophysics
- Other manifestations of new physics in the neutrino sector
  - astrophysics
  - cosmology